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Annex C — Methodological and Validation Plan for a Second-Generation N-Body Proof of Concept

Purpose

This annex defines a second-generation proof-of-concept methodology intended to evaluate whether the Quantum Hash Descriptor (QHD) framework can be coupled to a scientifically rigorous trajectory propagation layer for regular and irregular planetary motion. The annex is motivated by the fact that the initial Earth-only proof-of-concept and the subsequent heliocentric N-body extension demonstrated reproducible validation workflows against JPL Horizons, but did not yet achieve ephemeris-grade trajectory accuracy [cite:32][cite:99][cite:112][cite:128].

The objective of this annex is therefore not to claim that QHD already delivers perfect trajectory simulation. Rather, it defines the methodological conditions under which that claim could be tested rigorously, falsified if unsupported, and progressively strengthened if supported by evidence [cite:82][cite:83][cite:96].

Scientific framing

The current QHD manuscript provides a deterministic identity, serialization, and provenance architecture based on state representation, entropy normalization, energetic scaling, temporal indexing, and SHA3-256 hashing [cite:1]. That architecture is valuable for object identity and traceability, but trajectory fidelity depends on an additional dynamical layer capable of reproducing high-precision orbital motion under realistic physical assumptions [cite:32][cite:115][cite:119].

Accordingly, the second-generation proof of concept should be framed as a coupled system with two distinct components:

- A **dynamical propagation layer**, responsible for computing the trajectory under declared force models and integration policies [cite:119][cite:121].

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- A **QHD identity layer**, responsible for encoding each propagated state into a reproducible descriptor and a cryptographic hash for validation, provenance, and cross-platform synchronization [cite:1][cite:3][cite:12].

This separation is methodologically important because it prevents over-attributing orbital accuracy to the descriptor layer itself while still allowing QHD to play a central role in validation and traceability [cite:96].

Rationale for a second-generation N-body design

The first proof-of-concept comparison against JPL Horizons produced position errors on the order of hundreds of thousands of kilometers for Earth over a one-year interval, even after a simplified heliocentric N-body correction was introduced [cite:112][cite:128]. This indicates that the dominant limitations are not resolved by merely adding a few perturbing bodies within a simplified formulation [cite:128].

A more rigorous validation design must therefore address the full set of factors known to influence ephemeris-quality propagation, including barycentric consistency, force-model completeness, time-scale consistency, physically correct gravitational parameters, appropriate numerical integration, and transparent benchmarking against authoritative reference ephemerides such as DE440 or DE441 and JPL Horizons [cite:32][cite:114][cite:115].

Methodological architecture

System layers

The second-generation proof of concept should be organized into the following methodological layers:

Layer	Function
Reference ephemeris layer	Provides authoritative benchmark states from JPL Horizons / DE440 / DE441 [cite:32][cite:99][cite:115]
Dynamical propagation layer	Computes candidate trajectories under declared N-body dynamics [cite:119][cite:121]
QHD state-construction layer	Builds $P_0(t)$, entropy, descriptor, and metadata for each propagated epoch [cite:1]

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Canonical serialization layer	Produces stable machine-readable state records [cite:1][cite:94]
Validation layer	Compares propagated states to reference ephemerides using predeclared metrics [cite:96]
Provenance layer	Hashes and chains state records for reproducibility and auditability [cite:1][cite:12]

This architecture ensures that trajectory validation and informational identity remain coupled but analytically distinguishable [cite:96].

Dynamical model requirements

A scientifically serious second-generation proof of concept should include at least the following dynamical features:

- Full **N-body gravitational propagation** rather than a two-body or quasi-two-body approximation [cite:119][cite:121].
- A **barycentric or otherwise reference-consistent formulation** aligned with the benchmark ephemeris [cite:115].
- Use of **gravitational parameters consistent with JPL astrodynamic references** [cite:114][cite:115].
- A declared **time scale**, such as TDB or a rigorously mapped equivalent, consistent with the reference vectors [cite:32][cite:115].
- A high-quality numerical integrator with declared step-size control or adaptive strategy appropriate to the problem class [cite:119][cite:121].
- Explicit treatment of any additional effects required for the chosen bodies, such as relativistic corrections, non-spherical gravity, or non-gravitational perturbations where relevant [cite:115][cite:121].

Without these elements, the experiment may still be useful as a developmental test, but it should not be interpreted as a decisive validation of high-fidelity trajectory simulation [cite:96].

Validation targets

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The proof of concept should validate both regular and irregular trajectory classes rather than testing only one benign orbital regime. A recommended validation set is shown below.

Class	Candidate object	Validation role
Regular inner-planet trajectory	Earth [cite:99]	Baseline terrestrial benchmark
Regular inner-planet trajectory	Mars [cite:99]	Different orbital eccentricity and geometry
Regular outer-planet trajectory	Jupiter [cite:99]	High-mass outer-planet benchmark
Irregular or strongly perturbed case	Mercury or small-body case [cite:115][cite:121]	Sensitivity to additional corrections

Earth remains the correct base case because it is already partially implemented in the current validation chain [cite:112][cite:128]. Mars and Jupiter expand the test set across a broader dynamical range, while an additional irregular or more sensitive case prevents the validation from being tuned only to near-circular, well-behaved trajectories [cite:119][cite:121].

Data sources and benchmark policy

The benchmark trajectories should be derived from JPL Horizons or directly from DE440/DE441-consistent sources, with all data requests frozen and archived as part of the validation package [cite:32][cite:99][cite:115]. Each benchmark retrieval should declare:

- Target body.
- Center body or barycenter definition.
- Reference frame.
- Time scale.
- Output units.
- Step size.
- Start and stop epochs.
- Ephemeris source version where available [cite:32][cite:99][cite:115].

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This policy is essential because validation cannot be considered rigorous if the benchmark itself is underspecified or changes silently between runs [cite:96].

QHD integration policy

At each propagated epoch, the proof of concept should compute a QHD state record associated with the dynamical state. The following should be stored for each epoch [cite:1][cite:12]:

- State vector $(\vec{r}, \vec{v})$.
- Time stamp in the declared scale.
- Reference frame and units.
- Dynamical model version.
- QHD descriptor components.
- Canonical JSON serialization.
- SHA3-256 digest.

This requirement turns the proof of concept into more than a pure orbital propagation experiment. It demonstrates whether QHD can operate as a rigorous provenance and validation layer for a higher-fidelity orbital engine [cite:3][cite:12].

Metrics and acceptance criteria

The validation plan should define metrics before any claim is made. At minimum, the following quantities should be computed for each target and interval [cite:96]:

Metric	Purpose
Position RMSE	Global trajectory agreement
Maximum position error	Worst-case deviation
Velocity RMSE	Dynamical consistency
Maximum velocity error	Peak divergence
Energy drift	Numerical stability diagnostic

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Angular momentum drift	Integrator consistency diagnostic
Hash reproducibility rate	QHD determinism check

The first-generation and simplified N-body experiments showed Earth position RMSE values around 401,812 km and 401,544 km respectively, indicating that the present developmental implementation is far from ephemeris-grade agreement [cite:112][cite:128]. A second-generation proof of concept should therefore define substantially stricter acceptance bands before any claim of high-fidelity simulation is advanced [cite:96].

The acceptance logic should follow this sequence:

1. Validate numerical reproduction of the benchmark query itself.
2. Validate the dynamical model against the benchmark trajectory.
3. Validate QHD descriptor reproducibility for the propagated epochs.
4. Validate cross-run and cross-environment determinism of the serialized state and digest [cite:55][cite:57][cite:96].

Experimental protocol

A recommended experimental workflow is the following.

Phase 1: Reproducible benchmark assembly

Freeze all JPL Horizons benchmark queries and archive the returned vectors and metadata for Earth, Mars, Jupiter, and the selected irregular test case [cite:32][cite:99]. This prevents benchmark drift and allows later independent repetition [cite:96].

Phase 2: Barycentric N-body propagator construction

Implement a full N-body propagator using a declared force model, declared gravitational parameters, declared frame, and declared time scale. The implementation should be able to run from the same initial state used by the benchmark and should document whether planetary states are integrated jointly or supplied from an external ephemeris [cite:114][cite:115][cite:119].

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Phase 3: Numerical verification

Check the integrator independently by monitoring energy and angular momentum behavior where applicable. This phase is necessary because a model can appear close to a reference trajectory for short intervals while still being numerically unstable or physically inconsistent [cite:119][cite:121].

Phase 4: Benchmark comparison

Compare propagated states against JPL Horizons over multiple horizons, such as 30 days, 180 days, and 365 days, for each selected object. Short- and medium-horizon evaluations help distinguish initialization issues from cumulative dynamical drift [cite:32][cite:99][cite:96].

Phase 5: QHD state capture

At each propagated epoch, generate the corresponding QHD state record, descriptor, serialization, and hash. This demonstrates that QHD can index, verify, and chain the trajectory states produced by the dynamical layer [cite:1][cite:12].

Phase 6: Independent repetition

Repeat the full experiment in a second implementation or execution environment, then compare both the trajectory metrics and the QHD digests. This is a critical scientific step because reproducibility is one of the main claims of the QHD framework [cite:55][cite:57][cite:96].

Regular and irregular trajectory interpretation

Regular trajectories in this annex refer to bodies whose motion is comparatively well behaved under long-established planetary ephemeris frameworks, such as Earth, Mars, and Jupiter [cite:99][cite:115]. Irregular trajectories refer here to cases that are more sensitive to perturbations, stronger relativistic effects, non-circular geometry, or more demanding modeling assumptions, rather than implying chaos in an unrestricted mathematical sense [cite:115][cite:121].

This distinction matters because a validation strategy limited to Earth alone can overstate success by focusing on a comparatively familiar orbital regime. A broader validation set makes it much harder to overfit the methodology to a single favorable case [cite:96].

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Interpretation of success and failure

A successful second-generation proof of concept would not merely reduce the current Earth error metrics. It would demonstrate that the coupled dynamical-plus-QHD system can:

- Reproduce benchmark ephemerides within declared and materially improved tolerance bands [cite:32][cite:99].
- Maintain stable numerical behavior under the declared integration policy [cite:119][cite:121].
- Produce deterministic QHD records for every propagated epoch [cite:55][cite:57].
- Preserve reproducibility across multiple runs and environments [cite:96].

Conversely, if the dynamical layer still produces large benchmark discrepancies, the scientific conclusion should be that QHD remains validated primarily as an identity and provenance framework rather than as a standalone high-fidelity propagation engine [cite:1][cite:112][cite:128]. This is a meaningful result, not a failure of the broader program, because it still establishes a rigorous role for QHD in validation and archival integrity [cite:3][cite:12].

Deliverables

A complete second-generation proof-of-concept package should contain the following items.

Deliverable	Role
Frozen benchmark vector datasets	Reference truth set [cite:32][cite:99]
Dynamical model specification	Declares force model and assumptions [cite:119][cite:121]
Gravitational parameter table	Ensures consistency with reference constants [cite:114][cite:115]
Numerical integration report	Documents solver behavior and stability
Validation metrics tables	Quantifies performance [cite:96]
Epoch-by-epoch QHD records	Demonstrates informational traceability [cite:1][cite:12]
Reference hashes and conformance vectors	Enables independent reproduction [cite:55][cite:57]
Final validation report	States whether the claim is supported, limited, or rejected [cite:96]

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Annex status

This annex may be used as a methodological and validation appendix for the next-stage development of QHD. It is suitable for inclusion in a scientific manuscript, proof-of-concept dossier, or institutional technical package where the goal is to test whether QHD can be coupled to a sufficiently rigorous N-body propagation framework for trajectory validation under scientifically defensible conditions [cite:82][cite:83][cite:96].

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